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Prediction of an H₂+ Satellite Feature at 1100 Å
In the Spectra of DA White Dwarf Stars

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ABSTRACT

We have investigated the ultraviolet spectrum of pure H DA white dwarf atmospheres in an exploration of the behavior of various features at 1400 and 1600 Å which have been identified as satellites of the Lyman- α line of hydrogen. We find that the strength of these features, particularly the 1400 Å satellite feature, is strongly dependent on the treatment of broadening mechanisms for this feature for which the theory is inadequate. If these features have been correctly identified, there should be an additional observable satellite feature at 1100 Å.

Subject headings: stars: white dwarfs - ultraviolet: spectra
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I. INTRODUCTION

Ultraviolet satellites, hydrogen absorption features which aren't Lyman lines, in DA white dwarfs have a short but interesting history. In 1980, Greenstein published an IUE spectrum of DA white dwarf 40 Eri B with an unexpected, unexplained ultraviolet absorption feature at 1400Å. The feature was tentatively identified as Si IV. (Not long afterward, a feature at 1600Å was discovered in several DA spectra. See Wegner 1984a.) From the large number of DA spectra now known to have these features, it is probable that these features are ubiquitous among DAs with effective temperatures on the range 10000-20000K. Until 1984, no satisfactory identification of the features was made. Si IV, Si II, Mg I, C I, and Ca II had been proposed as the source of the features. (See Wegner 1984a and Vauclair, Weidmann, and Koester 1981.) Holm et al. (1984) proposed that the 1600Å feature was a satellite to Lyman- α due to quasimolecular absorption by H₂. Koester, et al. (1985), and Nelan and Wegner (1985) have since confirmed that suggestion, and in addition, identified the 1400Å feature as due to quasimolecular absorption by H₂⁺. The model spectra they calculate more or less fit the observations, but it is apparent from their papers that

the physics of the broadening of satellite lines is not understood well enough (or perhaps calculated carefully enough) for an exact fit. The 1400Å feature in Figure 4 of Nelan and Wegner, calculated for $T_{\text{eff}}=13000\text{K}$, $\log g=8.0$, has an equivalent width of 30Å, roughly three times the equivalent width observed in DAs of that temperature. A visual inspection of Figure 2 in Koester et al., as compared with the observations of star Wolf 485A by Wegner (1984b), indicates that the models of Koester et al. produce Lyman- α profiles that are far too broad to match observations.

Stewart, Peek, and Cooper (1973), in their discussion of the satellite feature at 1400Å, note that there are several inter-proton distances where there is an extremum in the difference in energies between the first electronically excited state and the ground state of the H₂⁺ molecule. At the energies corresponding to the extrema, the absorption produced by the molecule is enhanced; the resulting peak in the absorption coefficient is called a satellite. In addition to the 1400Å satellite, they predict several other satellites of the same origin at shorter wavelengths. Our principal motivation in this paper is to investigate whether these shorter wavelength satellites would be observable. We find that under very reasonable

assumptions, a satellite absorption feature at a wavelength of about 1100Å should be quite prominent in DA white dwarf spectra in the range $10000 < T_{\text{eff}} < 22000\text{K}$. The observation of such a feature by the Voyager spectrometers or by the Hopkins Ultraviolet Telescope (HUT) would confirm the identification of the 1400Å feature as a quasimolecular H₂+ satellite, even if we do not understand the broadening mechanisms well enough to match the profiles of the satellites individually in an exact way.

II. METHODS

Stewart, Peek, and Cooper predict satellites at 1404.9Å, 1240.5Å, 1233.5Å, 1106.5Å, 1018.0Å, and 965Å. Unfortunately, they consider only thermal broadening of the satellites, and actually give absorption profiles only for the first three satellites. Knowing that for a purely Doppler profile of width $\Delta\nu_0$ the peak absorption is

$$\alpha_{\nu\nu} = \frac{\pi^2 e^2 f}{m_C \Delta\nu_0} \quad (1)$$

oscillator strengths f for the first three satellites can easily be found from the absorption coefficients that Stewart, Peek,

and Cooper give. For the remaining three satellites, those on the blue wing of Lyman- α , we assumed the oscillator strengths could be approximated as the average of the three known f values. This is the best that we could do without redoing the atomic physics ourselves, and in Section III we show that the 1100Å feature should still be present at an observable strength even if we have overestimated the oscillator strength for the transition by an order of magnitude.

The Doppler widths of the features, at typical DA temperatures, are all very small, about 0.1Å. Doppler broadening alone is not sufficient to account for the several Å equivalent width of the observed 1400Å features. We included Stark broadening in the profiles by assuming that the Stark profiles of the features could be approximated by scaling down the Stark profile of Lyman- α by the ratio of oscillator strengths for the satellite and Lyman- α transitions. In other words, the half-width of the satellite features was assumed to be the same as the half-width of Lyman- α , though the central intensities are different. This seemed like a reasonable starting assumption. Previous papers on this feature have taken various approaches to the broadening of this feature, with Nelson and Wegner (1985 and private communication from G.W.) apparently only including the Doppler profiles

from Stewart, Peek, and Cooper (1973), and with Koester, et al., (1985) calculating the broadening from the atomic physics, using a "unified" approach to quasimolecular pressure broadening.

However, even with Stark broadening included in the model atmosphere calculations we did with the ATLAS model-atmospheres program, at 15000K, the 1400Å feature had an equivalent width of only about 1Å, still far too small. Conceding that we did not understand the broadening mechanisms at work, our next step was to increase the width, not the total ξ -value, of the absorption produced by the satellite feature. We did this by retaining the same central intensity in the Stark profile, but making it broader. We recognize that this introduction of artificial broadening is an ad hoc treatment, but we feel it is justified given the rather primitive state of the broadening theory for these satellite features. An artificial increase in the half-width of the Stark profile by a factor of 25 was sufficient to produce an equivalent width for a model with $T(\text{eff})=15000\text{K}$, $\log g=8.0$ to match the observed equivalent width of Wegner's (1984) spectrum of Wolf 485A. The atmospheric parameters for W485A are taken from Digel and Shipman (1984). Then we applied the same broadening factor to the other satellites of the same origin.

III. RESULTS

Figure 1 compares the IUE spectrum of Wolf 485A from Wegner (1984) with a computed spectrum for $T(\text{eff}) = 15000\text{K}$, $\log g = 8.0$. W485A has $T(\text{eff}) = 14,600\text{K}$ and $\log g = 8.0$ (Digel and Shipman 1984). The computed spectrum has been "averaged" to simulate the 7Å bandwidth of the IUE spectrometer. The broadening factor of the 1400Å feature in the model was chosen to make the equivalent widths of the features match, as explained in Section II. While the observations are a bit noisy, we note that the observed feature is shallower and broader (in the sense that the full width at half central depth is higher), at a somewhat shorter wavelength, and more asymmetric than the calculated spectrum. We believe that this illustrates inadequacies in the atomic physics which is presently available.

The models resulting from applying the 1400Å feature broadening factor to all the satellites showed that only the one at 1100Å should be strong enough to show up with an observable width. In fact, it should be quite prominent for $10000\text{K} < T(\text{eff}) < 22000\text{K}$. Figure 2 shows the 1100Å feature from the same model and broadening factor used in Figure 1. (In this figure,

Insert figure 1

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however, no attempt was made to simulate the finite bandwidth of a spectrometer.)

The equivalent width of the 1100 \AA feature is 6 \AA at 10000K, rises to 16 \AA at 15000K, and falls to 6 \AA again by 22000K. Figures 3 and 4 show how the computed widths of the 1400 and 1100 features depend on temperature. Figure 3 also includes published observations of the 1400 \AA feature for comparison. Note that in Figure 3, the computed widths are for $\log g=8$, while of course, the observed stars do not all have $\log g=8$. The models agree fairly well with the observations, particularly at higher temperatures. While the data are sparse, the calculated maximum in the equivalent width vs. temperature relation does not seem to fit the data; additional data would be useful here.

Figure 5 shows the gravity dependence of the 1100 and 1400 \AA features. For the 1100 \AA feature, the dependence of the equivalent width of the feature on gravity is not simple; the relationship is complicated by the presence of Lyman lines on either side of the feature, which makes the "continuum" shape very temperature and gravity dependent. The 1400 \AA feature, however, depends monotonically on gravity, since it is located where the continuum level is not strongly dependent on gravity. However, the gravity

dependence of the strength of the feature is still complex. Before either of these features can be used as a gravity diagnostic for a star, a better understanding of the broadening and a very reliable estimate of $\tau(\text{eff})$ would be needed.

The oscillator strength we used for the 1100 \AA feature was the average of the oscillator strengths for the three satellites on the red wing of Lyman- α . Without going into the atomic physics, we have no idea of the validity of this assumption, but we found that if we overestimated the oscillator strength by an order of magnitude, the equivalent width of the feature would be 3.2 \AA instead of 16 \AA at 15000K, $\log g = 8$. 3.2 \AA is still within the realm of detectability. The ξ -values derived from Stewart, Peek, and Cooper for the three long-wavelength satellites differ by a factor of 18. Thus even if the ξ -value of the 1100 \AA satellite were to be a factor of 1.3 smaller than the smallest ξ -value of a longer wavelength satellite, it would still have an equivalent width of 3.2 \AA (for $\tau(\text{eff})=15000\text{K}$) and would be detectable with spectroscopic instruments of modest resolution such as VOYAGER.

It should be noted that we also followed Nelan and Wegner and Koester, et al in using the absorption coefficient from

Sando and Wormhoudt (1973) to model the 1600 \AA feature. The 1600 \AA feature is intrinsically very broad, and is not made much broader with the inclusion of Stark broadening. Our results for this feature were therefore not dependent on broadening mechanisms, and they agreed with those of Nelan and Wegner and Koester et al.

IV. CONCLUSIONS

Given that the assumptions made here about oscillator strengths and broadening mechanisms are reasonable, the 1100 \AA feature should be prominent in the spectra of many white dwarfs. Some good candidates for observations by HUT or Voyager are 40 Eri B, W485A (EG99), EG144, and EG162. All have effective temperatures at which the 1100 \AA feature should be strong and all are among the brightest DAs.

Also, this work serves to point out how inadequate our understanding of satellite line broadening mechanisms is. Progress along theoretical fronts would help the models tremendously. In this paper, we could attempt to match only the equivalent widths of the satellite features. Much more work on satellite line broadening mechanisms remains before we can try

to match line profiles.

Given the level of our understanding of these satellites, it is probably premature to use the features as an indicator of surface gravity as Nelan and Wegner propose. The 1100 \AA feature trapped between two Lyman lines probably holds no promise as a gravity indicator. The 1400 \AA feature may indeed become a useful gravity indicator, but a glance at Figure 3 reveals that temperature dominates gravity by far in determining the strength of the feature, since all the stars fall near the log $g=8$ curve.

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FIGURE CAPTIONS

Figure 1 - Comparison of an IUE spectrum of Wolf 485A (14,600K, $\log g = 8.0$) from Wegner (1984) with a computed spectrum for $T(\text{eff})=15000\text{K}$, $\log g = 8.0$. The model spectrum has been averaged to simulate the 7Å resolution of the IUE spectrum.

Figure 2 - The 1100Å feature corresponding to the model of

Figure 1. The equivalent width of the feature is 16Å. The broad, strong depressions at 1216Å and 1032Å are Lyman- α and Lyman- β respectively.

Figure 3 - The temperature dependence of the equivalent width of the 1400Å feature. Solid curve, from models. Symbols have the following meanings: X, from models; circle, Holm et al. (1985); triangle, Wegner (1984b); square, Sion et al. (1984); G, Greenstein (1980).

Figure 4 - The temperature dependence of the equivalent width of the 1100Å feature, from models. X indicates models calculated.

Figure 5 - The gravity dependence of the 1100Å and 1400Å

features. For the 1100 \AA feature, the equivalent widths are 16 \AA for the $\log g = 7.5$ model, 17 \AA for $\log g = 8.0$, and 15 \AA for $\log g = 8.5$. For the 1400 \AA feature, the widths are 8.3 \AA (7.5), 11.9 \AA (8.0), and 14.0 \AA (8.5).

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